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Acoustic Wave Propagation in Urban Environments

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Abstract

The United States Army is continuously improving upon its situational awareness in operational environments. This is particularly difficult in an urban scene because line of sight is limited and because the acoustic interaction between and over the top of the buildings is not yet fully understood. Once this is fully understood the acoustic detection, classification, and localization can be accomplished through the use of well-placed acoustic sensors. This work focuses on application of acoustic wave-propagation computations to investigate the effects of urban environments on sound propagation. The objective of this work is to present models and wave-field results that illustrate in detail acoustic propagation and its interactions with buildings in an urban environment. Our computations are performed by a three-dimensional (3D) finite-difference time-domain code. This code operates on high-performance computers to create high fidelity data sets of acoustic waves propagating in urban scenes. These scenes are acquired from urban modeling templates produced by the Army Materiel Systems Analysis Activity (AMSAA) with areas distinguished by Urban Terrain Zones. This study examines a single source propagating through a portion of the AMSAA "Small City Periphery" urban template. The results show how acoustic waves propagate from a source through urban scenes. The propagation contains multi-path reflections between buildings that channel sound energy down streets, and wavefronts that travel between and over the tops of buildings. The results show that while some sound may travel over two to three story buildings before returning to ground level, a majority of the sound energy propagates between the buildings. We conclude that 3D finite difference time domain analysis is a practical tool for investigating acoustic propagation and its interactions with buildings in an urban environment.

1. Introduction

The United States Army is continuously improving upon its situational awareness in operational environments. This is particularly important in urban terrain where line of sight can be limited by closely spaced buildings. Acoustic detection, classification, and localization can be accomplished through the use of well-placed acoustic sensors, yet the complexity and lack of understanding of sound propagation through urban environments limits effective use of acoustic signals. This work focuses on application of acoustic wave-propagation computations to investigate the effects of urban environments on sound propagation.

2. Overview

An important issue within the US Army is minimizing the injury and mortality rate of our soldiers when they go into battle. This involves being proactive in the hunt for new technology that will help to increase our situational awareness and protect our troops. High performance computing (HPC) can support technology development by high-fidelity simulations of physical processes in realistic environments. In this paper the topic is high-fidelity simulations of sound propagation in urban environments. The focus is on acoustic simulations in exterior urban environments to promote understanding of how sound waves move through this environment and interact with buildings and other obstructions. Such understanding will allow the Department of Defense (DoD) to formulate rules for acoustic sensor placement and understand limitations on sensor performance for acoustic detection, classification, and localization of hostile forces.

The simulations are performed by finite difference time domain (FDTD) computations on high-performance computers, with input parameters derived from urban-terrain modeling templates produce Army Materiel Systems Analysis Activity AMSAA^[1]. AMSAA created

the templates in seven categories: commercial ribbon, residential sprawl and/or industrial areas, city core, outlying high-rise area, small city periphery, large city periphery, and older small urban area. The templates incorporate single or multiple categories and subcategories of UTZs, as classified by Liu and Ellefsen^[2]. The work reported here, which is in progress, will include simulations spanning multiple urban templates and UTZs in order to capture a wide range of line-of-site and non-line-of-site propagation conditions. Data processing^[3] will create statistics to characterize the propagation for acoustic sensor placement and performance decision support.

This paper presents acoustic propagation results of two models from the small-city periphery (SCP) template^[1], and provides background for the analysis presented in Reference 3. The results illustrate, in detail, sound waves and their interactions with buildings in the simulated SCP environments.

3. Computational Method

The FDTD computations operate in parallel on high-performance computers using FORTRAN 90. The computations solve the following partial differential equations^[4,5] to produce output quantities pressure p and particle velocity v :

$$\frac{\partial p}{\partial t} = -\rho c^2 \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} - Q \right) \quad (1)$$

$$\begin{aligned} \frac{\partial v_x}{\partial t} &= -\frac{1}{\rho} \left(\frac{\partial p}{\partial x} + \sigma v_x \right) \\ \frac{\partial v_y}{\partial t} &= -\frac{1}{\rho} \left(\frac{\partial p}{\partial y} + \sigma v_y \right) \\ \frac{\partial v_z}{\partial t} &= -\frac{1}{\rho} \left(\frac{\partial p}{\partial z} + \sigma v_z \right) \end{aligned} \quad (2)$$

where v_x , v_y , and v_z are the components of the particle-velocity vector; ρ is material density; c is speed of sound in the material; σ is the material flow resistivity; and Q is the dilatation-rate source. The method uses second-order finite differences in time and in space on a Cartesian variable staggered grid^[6], and an absorbing boundary condition^[7] at the model edges. Domain decomposition divides the structured grid into equal-sized blocks, and Message Passing Interface communications pass needed data between the blocks for processing and for saving wave-field data in files. The finite difference equations allow inhomogeneous material properties. The flow-resistivity terms are included to model porous media, and are assigned zero values for air nodes.

4. Model Parameters

The model parameters characterize two similar but different-sized acoustic models from the small-city periphery template. Figure 1 shows the plan view of the template, which is 750×750 m, and Figure 2 shows the two models' extents. Each is part of a model series created for statistical analysis. The first model, designated SCP02, extends 280 meters in the x and y directions and 60 meters in the vertical direction. The second, SCP750_02, extends 775 meters in the x and y directions and 160 meters in the vertical direction. Both have a horizontal ground surface. The SCP02 layout is within the black square in Figure 2, whereas the SCP750_02 job uses the entire area.

The small-city-periphery template consists of 2–3 story buildings, which are assigned heights in the acoustic models using 3 m per story. The SCP template contains a single UTZ, designated A2, which is made up of attached multistory buildings such as apartments and hotels on the edge of a city core.

The x , y location of the acoustic pulse is the same in both models—at the center of Figure 2. To accommodate a lateral variety of source locations within the larger-model series, the SCP template was extended to create a larger template. This was accomplished by forming a 3×3 matrix of the SCP template, with a 25-m roadway gap between them, as illustrated in Figure 3. The nine individual templates were arranged so that the four intersections between them did not repeat the same arrangement of corners. The portion of this 3×3 template utilized in the SCP750_02 model is outlined in Figure 3.

Each model contained two materials, air and a construction material, with the properties listed in Table 1. Both the ground and the template buildings were assigned the properties of the construction material. The flow resistivity, porosity, and tortuosity of the construction material approximate an acoustic reflectivity akin to that of asphalt^[4] or mortar. The porosity and tortuosity in Table 1 enter into calculations of effective density and wavespeed^[4] of the ground and building materials, which are input properties for the models. Cudney, et al.^[5], demonstrate the capability of this method and these materials for accurate reflection and propagation of air-borne sound.

Table1. Material Constants

Material	Density (kg/m ³)	Acoustic Wave Speed (m/s)	Flow Resistivity (Pa- / m2)	Porosity	Tortuosity
Air	1.2	347	N/A	N/A	N/A
Construction Materials	163.8	75.5	3.00E+07	0.1	3.2

In each model the source is just above the ground surface. The source locations and additional model parameters—peak source amplitude, number of time steps, time step, simulation length and grid size—are shown in Table 1. Input values for the dilatation rate produced the 609 and 30 kPa/m³ source amplitudes listed. Figure 4 shows the unit-less time series of the source and its energy spectrum. The time series is a Gaussian pulse with a 40-Hz center frequency. The energy in the signal is reduced by 40 dB below the peak at 91.6 Hz, which corresponds to a wavelength of 3.79 m for propagation in the air material. This ensures that the model has at least 10 nodes per wavelength at this short wavelength.

Table 2. Model Parameters

Job Name	SCP750_02	SCP02
(x, y, z) Source Location (m)	(389, 388, 1.3)	(143, 142, 1.1)
Peak Source Amplitude (kPa/m ³)	609	30
Number of Time Steps	8086	8193
Time Step (ms)	0.532	0.195
Simulation Duration (s)	4.30	1.60
(x, y, z) Node Spacing (m)	(0.321, 0.321, 0.321)	(0.118, 0.118, 0.118)

5. Job Parameters

The simulations were completed on the Engineering Research and Development Center (ERDC) XT3 using 256 processors (2007 upgrade, 2GB per processor). The information for both jobs is listed in Table 3.

Table 3. Computational Model Parameters

Job Name	SCP750_02	SCP02
Wall time	5 h 59 min.	6 h 21 min.
Processors	256	256
Number of Nodes	2.763e9	2.763e9

6. Results

The results of the acoustic job SCP02 are shown in Figures 5 and 6. Figure 5 shows a sequence of images of the acoustic pressure as it propagates out from the source and through the urban model. Figure 6 shows an analysis of the pressure signal from a single location in the model.

The Figure 5 images show key features of the propagation. Figure 5a illustrates the effect of the buildings on the wave fronts by the reflections off walls near to the source and diffractions around corners.

Reflections within passages between the narrower building offsets appear to guide or channel the sound energy, with diffractions around the far corners appearing to release the energy. Figure 5b shows that line-of-site and open areas appear to have relatively stronger pressure amplitudes, and obstructed areas have decreased amplitudes. While there are disruptions by the buildings of the wave spreading at ground level, the wave fronts spread over the buildings and back to the ground in an obvious radial pattern, although with distortion and loss of amplitude. At the later time in Figure 5c, the distinguishable wave fronts are giving way to incoherent multi-path patterns.

The signal and spectrogram in Figure 6 show characteristics of the first-arriving pulse and subsequent reflected pulses with time at the receiver location shown in Figure 5b. These pulses are indicated in Figure 6a and 6b as increased broadband energy in the spectrogram and as pressure spikes in the pressure versus time plot, each of which diminishes with time. The spectrogram shows the dominant energy centered around 40 Hz, which is the source frequency.

A sequence of pressure wave-field images from job SCP750_02, which covers the full area in Figure 2, is shown in Figure 7. Figure 7a shows the wave field at the same time as the data in Figure 5b, with the same pattern of spreading and reflected waves. In Figure 7b, which is at a time when the wavefront nears the edge of the model, the circular spreading pattern remains clear, but the reflected energy in the area near the source location shows mostly incoherent energy.

7. Conclusions

This paper has presented results from high-performance computations that illustrate detailed sound propagation and its interactions with buildings in an urban environment. The buildings are shown to reflect, guide, and diffract wave energy. The two and three story buildings in these simulations reflect the wave fronts incident on their facades, but allow energy to propagate over the rooftops and reach the ground on the opposite sides.

The results demonstrate the practicality of high-fidelity numerical computations for investigating acoustic wave fields in an urban environment. Because experimental data for urban acoustic wave fields are non-existent, these numerical data are necessary to develop decision support for acoustic sensor placement and performance.

Acknowledgements

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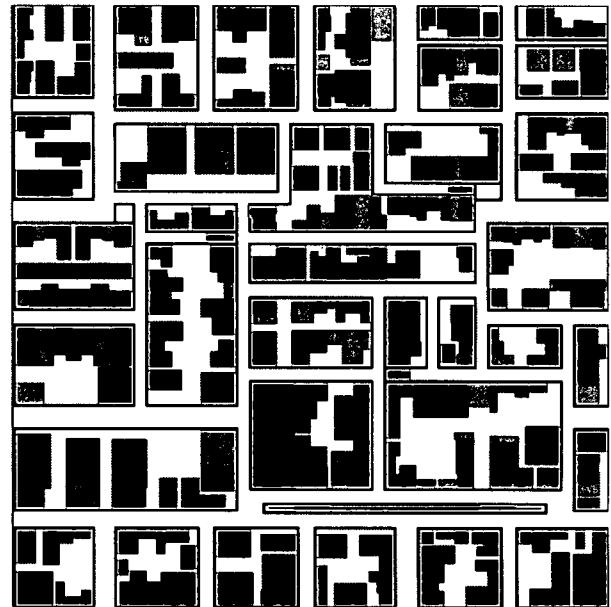


Figure 1. Small city periphery (SCP) template

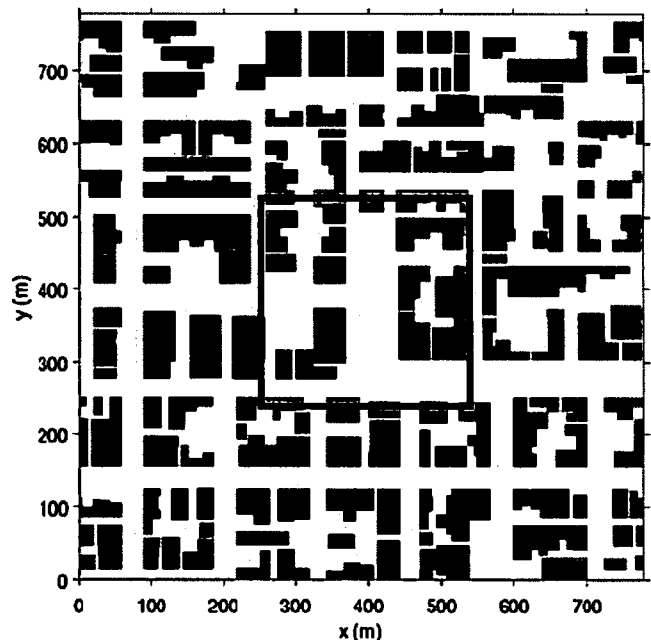


Figure 2. Aerial extents of models. The area of SCP02 is within the inner square and the area of SCP750_02 is the full plot.

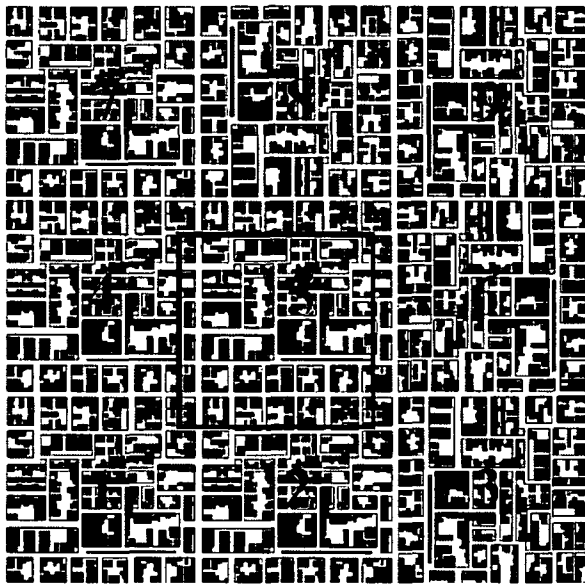


Figure 3. 3×3 matrix of small-city periphery templates, with outline showing Figure-2 extents

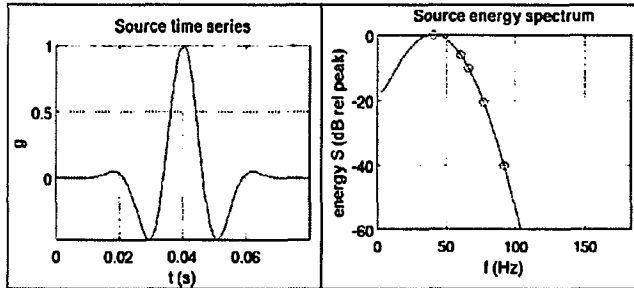


Figure 4. (a) Gaussian-pulse time series, and (b) corresponding energy spectrum relative to the peak, of the source inputs to models SCP02 and SCP750_02

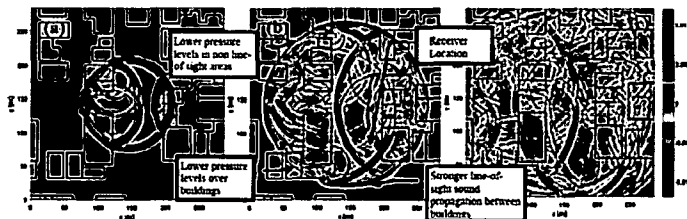


Figure 5. Snapshots of sound pressure, just above the ground and rooftops, during acoustic propagation in model SCP02. (a) $t = 0.23$, (b) $t = 0.39$, (c) $t = 0.55$ s. The color bar scale has units of Pa.

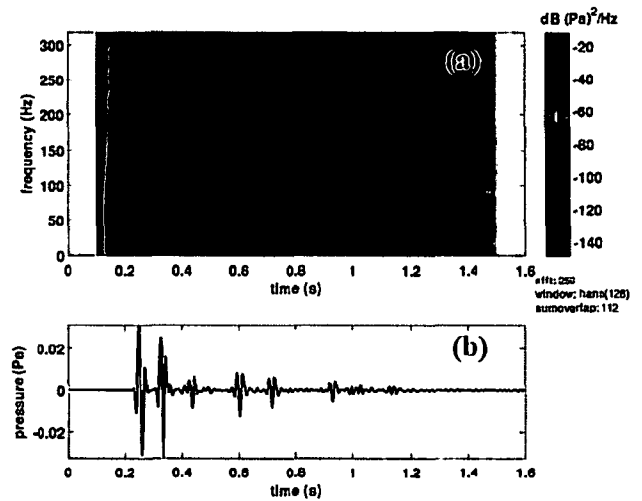


Figure 6. (a) Spectrogram and (b) acoustic pressure signal at location $(x, y, z) = (150, 50, 0.59)$ m in model SCP02

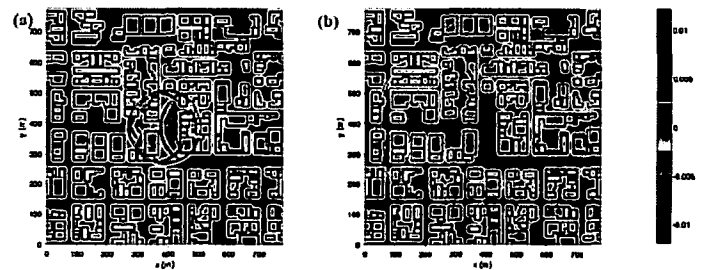


Figure 7. Snapshots of sound pressure, just above the ground and building roofs, for model SCP750_02. (a) $t = 0.23$, (b) $t = 1.06$. The color bar scale has units of Pa.